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THE MISSING LINK BETWEEN PRESSURE WAVES AND BREECHBLOWS

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The stability and reproducibility of the gun interior ballistic environment is one of the chief concerns of the ammunition designer. Investigators are now searching for an analytical "tool" to aid them in assessing the severity of potentially dangerous pressure waves. Of particular importance is the identification of processes responsible for an apparent transition to runaway pressure levels. Current efforts include application of state-of-the-art, two-phase flow, interior ballistic codes to breechblow environments. However, in most cases, excessive maximum pressures are not predicted to accompany severe → next page

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) pressure waves. Potential "missing links", such as transient burning rate enhancement and grain fracture, are postulated, and their impact on the overall ballistic cycle was discussed.

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I. INTRODUCTION

Numerous studies have been performed over recent years to determine the causes and controlling mechanisms responsible for the existence of pressure waves in gun chambers. A major motivation for most of these efforts has been that of charge design safety. As recently pointed out by Budka and Knapton[1] "...researchers have revealed one common characteristic associated with the occurrence of unexpected high pressure excursions - namely, the existence of strong pressure waves in the gun system." Yet many weapons with excellent safety records and quite acceptable performance reproducibility characteristics also exhibit a significant level of pressure waves. Hence, it becomes of extreme importance to the charge designer that a thorough understanding be developed with respect to those mechanisms responsible for the transition between acceptable and unacceptable ballistic behavior. This report is devoted to a discussion of the status of an on-going effort to identify those mechanisms responsible for excessive or even catastrophic gun pressures.

II. BACKGROUND

The problem of breechblows is of most concern to the U.S. Army with respect to the design of high performance artillery bag charges. A typical layout for such a charge is presented schematically in Figure 1. Principal

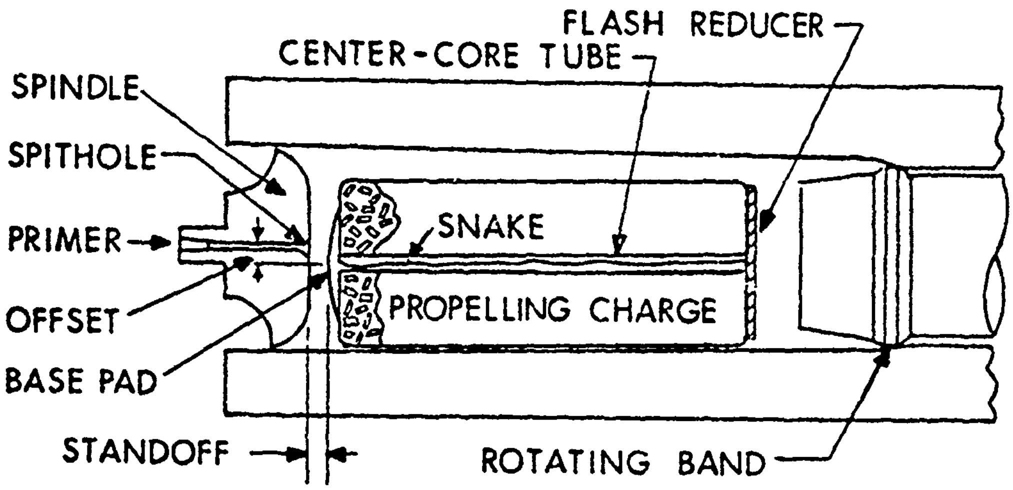

Figure 1. Typical Centercore-Ignited Artillery Propelling Charge

[1] *Budka, A.J. and knapton, J.D., "Pressure Wave Generation in Gun Systems: A Survey," BRL MR 2567, USA Ballistic Research Laboratories, Aberdeen Proving Ground, Maryland, December 1975* (AD #B008893L)

components of the charge include a base pad igniter (usually containing black powder or CBI*), a centercore igniter tube (containing additional igniter material), and a main charge (typically multi-perforated, triple-base, granular propellant). A cloth bag is employed to contain the charge, and other components such as a flash inhibitor or wear-reducing additive may be present. We postulate functioning of the charge to be described by the following sequence of events: The base pad igniter is initiated by the impingement of hot combustion products form a percussion primer. The base pad then ignites the centercore charge, and together they ignite nearby propellant grains. Combined igniter and propellant gases penetrate the propellant bed, convectively heating the grains and resulting in flamespread. During this process, the pressure gradient and interphase drag forces tend to accelerate the propellant grains, largely in the forward direction, thrusting them and any intervening elements against the projectile base. Upon stagnation, a reflected compression wave in the gas phase may be formed, its magnitude being subject to increase by the combined effects of reduction in free volume (due to bed compaction) and combustion in this low-porosity region.

If the charge functions as intended, smooth pressure-time curves as shown in Figure 2 are obtained. A pressure-difference history, formed by subtracting the pressure measured by a gage in the chamber wall near the initial position of the projectile base (hereafter identified as the chamber mouth) from the breech pressure as a function of time, reveals only the normal forward-facing gradient associated with motion of the projectile down the tube. On occasion, however, pressure-time histories as shown in Figure 3 are obtained. Strong longitudinal pressure waves are clearly manifested in the pressure-difference plot. Such phenomena have been traditionally associated with localized ignition of the propellant bed and thus may imply non-functioning or at least late functioning of the center-core charge. Whether this wave dissipates or grows is dependent on a complex interplay of events controlled by gas production rates, ullage, bed permeability and projectile motion. Thus, other factors in addition to proper functioning of the ignition train may be of importance. Finally, increases in maximum chamber pressure may or may not accompany such increases in pressure-wave dynamics, with extreme levels resulting in breechblows. Hence, a complete understanding of all processes involved in the growth of pressure waves is essential for safe and efficient design of high-performance artillery charges.

III. DISCUSSION OF THE PROBLEM

Recent Safety Analysis Techniques. Ever since the availability of recorded pressure-time data, investigators have viewed any irregularities in such curves with suspicion. With the advent of detailed, qualitative

*Clean Burning Igniter, a nitrocellulose-based ignition material

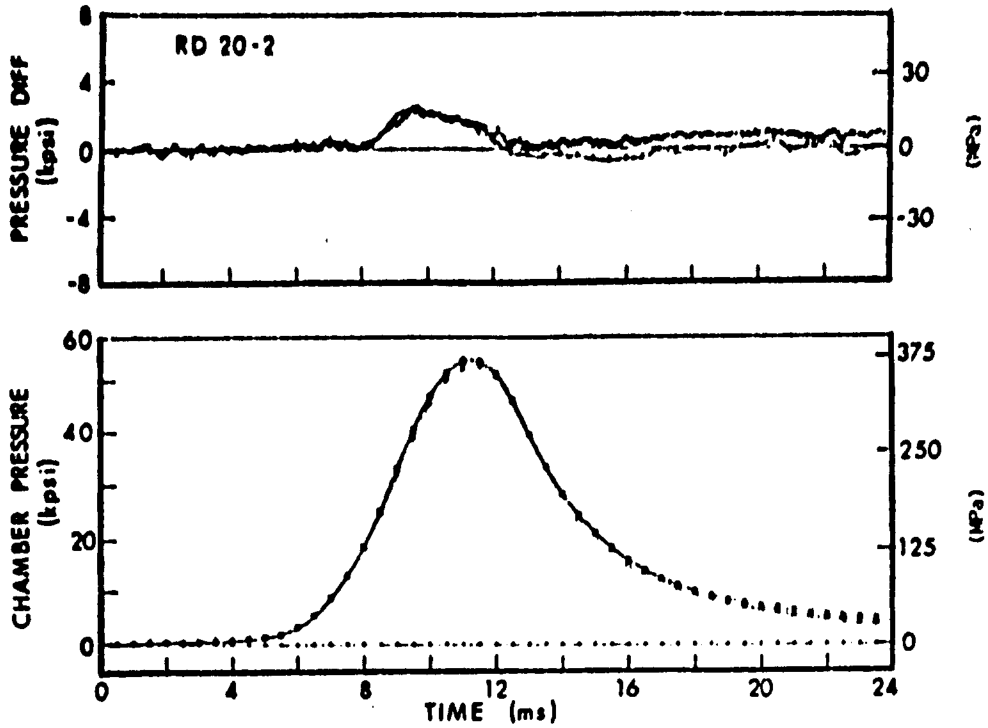

Figure 2. Pressure-Time and Pressure-Difference Profiles for a Properly-Ignited, High-Performance Charge

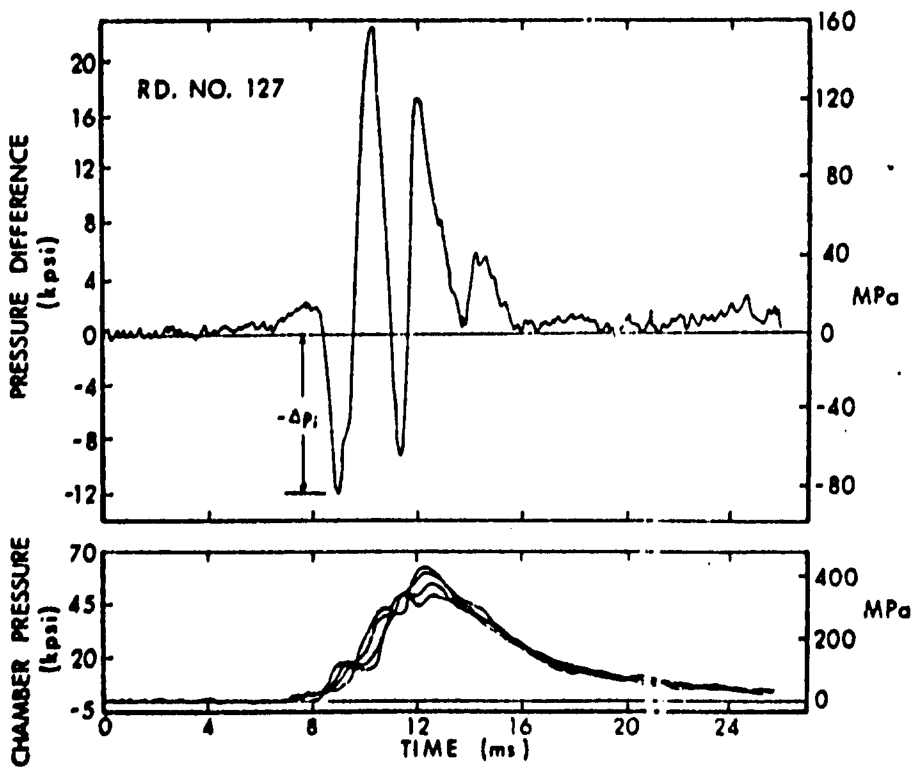

Figure 3. Pressure-Time and Pressure-Difference Profiles, Localized Base Igniter

explanations for the presence of pressure waves, the charge designer was provided with a physical basis for rejection of charges producing such irregularities. However, a quantitative rejection criterion still eluded the designer for some time. In 1972, the U.S. Navy ranked potential reduced charge designs for the 8-inch gun according to their accompanying initial reverse pressure difference ($-\Delta p_i$) levels[2], a measure of the severity of longitudinal pressure waves as depicted in Figure 3. Yet, no quantitative acceptability limit for $-\Delta p_i$ was established, as experience had shown that different systems could tolerate quite different levels of pressure waves. Then, in 1974, the first extensive study of the relationship between pressure waves and ballistic performance was provided by Clarke and May[3]. Motivated by a breechblow in the 155-mm, XM198 Howitzer, those studies were limited mainly to analysis of data acquired in this system. Nevertheless, significant trends were clearly observed. Increases in pressure wave levels (as measured in terms of the quantity $-\Delta p_i$) were shown to be accompanied by both increases in performance variability and, of more direct interest to the topic of this paper, increases in maximum chamber pressure (Figure 4). The study also revealed that this sensitivity of peak chamber pressure to pressure waves increased with loading density.

Largely as a result of these findings, a tentative safety analysis procedure was developed and has been undergoing evaluation as necessary data have become available. Essentially, the procedure can be summarized as follows:

(1) Charge design sensitivity firings are conducted to determine the relationship between $-\Delta p_i$ and maximum chamber pressure for that charge/weapon combination. Intentionally-defeated centercore charges may be included in this series to assure that data from a localized-ignition/high-pressure-wave firing can be obtained with a reasonable number of tests.

(2) A failure criterion is identified, usually in terms of some maximum permissible chamber pressure, dictated most often by breech or payload failure levels.

(3) This failure level is re-interpretated in terms of a $-\Delta p_i$ level, determined from the sensitivity curve developed in Step (1).

[2] *Horst, A.W. and Haukland, A.C., "Gun Interior Ballistics: 1972 Annual Report," IHTR 386, Naval Ordnance Station, Indian Head, Maryland, April 1973.*

[3] *Clarke, E.V., Jr. and May, I.W., "Subtle Effects of Low-Amplitude Pressure Wave Dynamics on the Ballistic Performance of Guns," 11th JANNAF Combustion Meeting, CPIA Publication 261, December 1974, pp. 141-156.*

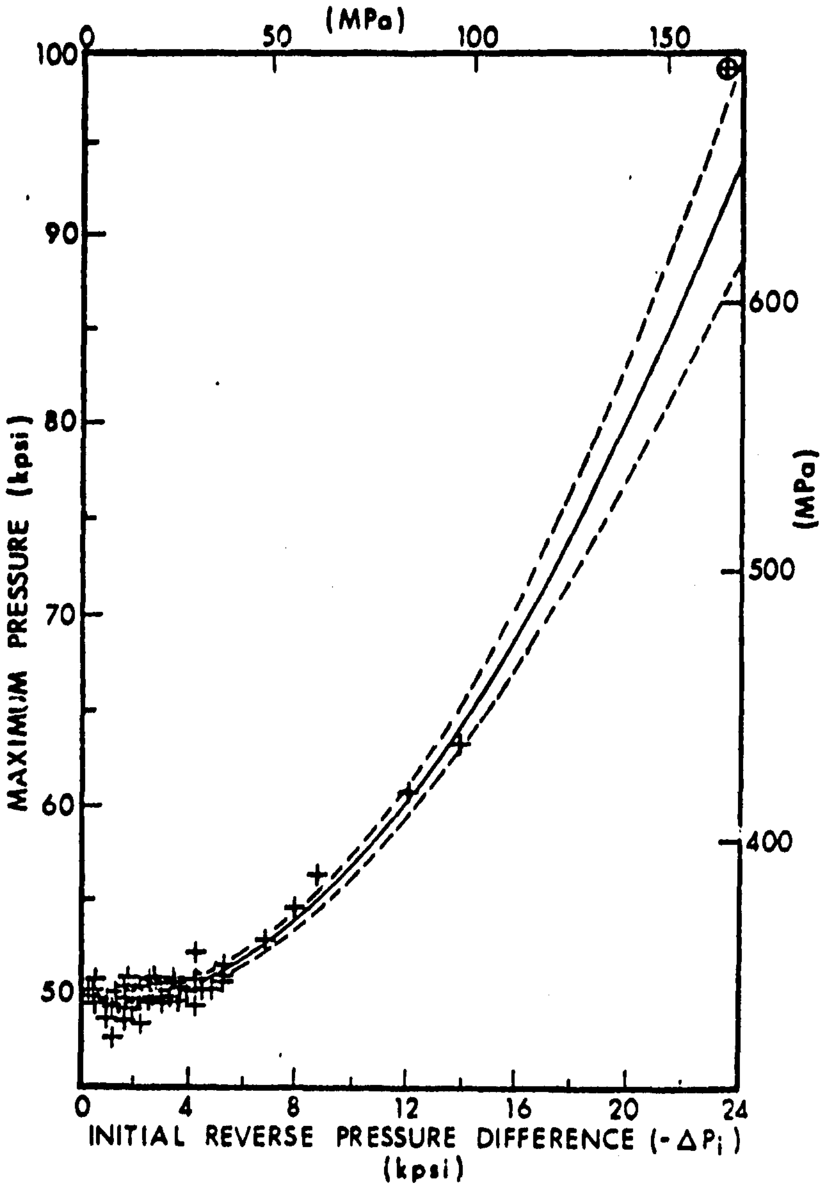

Figure 4. Correlation of Initial Pressure Wave Amplitude with Maximum Chamber Pressure (from Ref. 3)

(4) A population of firing data is then obtained which is believed to be representative of "real-world" propelling charges, typical of those to be fielded for use.

(5) The probability of failure (as defined in Step (3)) can then be statistically determined with respect to the distribution of $-\Delta p_i$ values from Step (4).

Thus a $-\Delta p_i$ failure level tailored to the sensitivity of the particular system of interest is employed.

Application of this procedure can be described briefly with respect to the 175-mm, M107 Gun. The relationship between $-\Delta p_i$ and maximum chamber pressure for M86A2 (Zone 3) charges fired in the M107 Gun, based on charge design sensitivity firings, is presented in Figure 5. A $-\Delta p_i$ failure criterion can also be identified on this curve, corresponding to a known breech failure pressure level. Figure 6 then presents the cumulative distribution of $-\Delta p_i$ levels for a data base considered to represent a typical population of "real-world" charges. The probability of achieving the $-\Delta p_i$ failure level, as determined using Kolmogorov-Smirnov statistics and two different population distribution functions, is presented in Figure 7. While confidence levels associated with this conservative statistical procedure are quite low, the prediction of one failure in about half a million firings compares

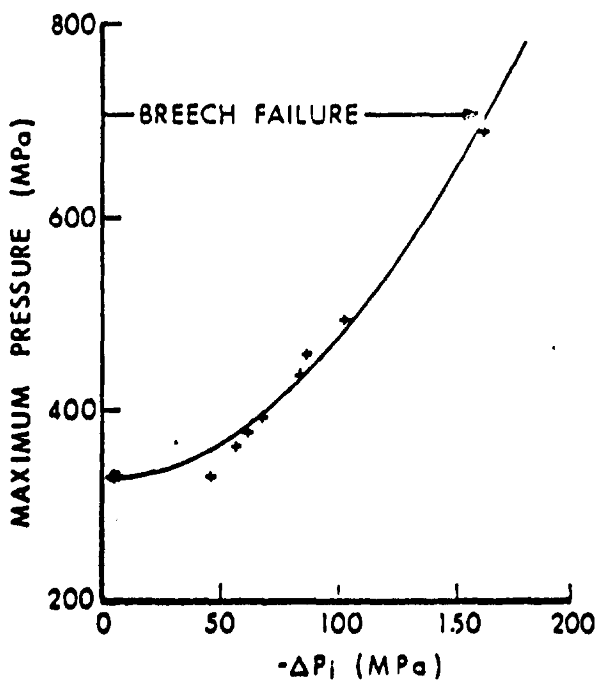

Figure 5. Pressure Wave Sensitivity for the 175-mm M107 Gun (M86A2 (Zone 3) Propelling Charge)

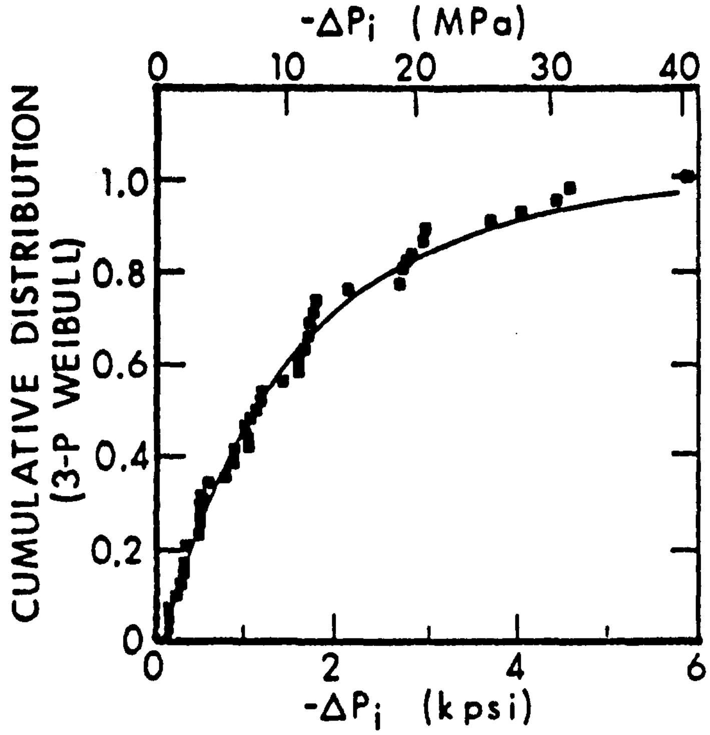

Figure 6. Distribution of Pressure Wave Amplitudes for the 175-mm, M107 Gun (M86A2 (Zone 3) Propelling Charge)

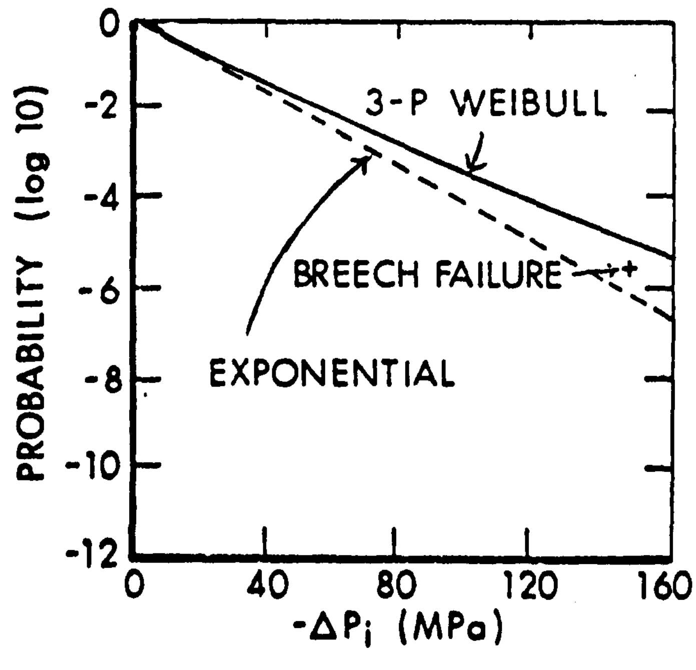

Figure 7. Probability of High Amplitude Pressure Waves for the 175-mm, M107 Gun (M86A2 (Zone 3) Propelling Charge)

quite favorably with historical data of half a dozen breechblows in some two and one-half million firings to date. This agreement, although satisfying, must be considered somewhat fortuitous.

Validity of the $-\Delta p_i$ Criterion. Recently, two serious questions were raised regarding the validity of this approach. First, do the procedures we follow to obtain the sensitivity with a finite number of rounds (e.g., defeating the centercore charge) yield results truly applicable to "real-world" charges - or have we simply obtained data on a new and different charge? Second, and just as potentially damaging to the usefulness of the procedure, are there other factors (e.g., conditioning temperature) that significantly alter this $-\Delta p_i$ versus P_{max} relationship for a given charge assembly?

One has available two avenues of attack for answering questions about the validity of this procedure for safety analysis. First, a statistically-based evaluation can be developed by simply increasing the sample sizes comprising our data bases. Though expensive, firing programs are underway to expand our knowledge on the subject in this way; however, completion of the effort will take some time. Concurrently, state-of-the-art interior ballistics modeling techniques are being employed to identify all potential propellant-related breechblow mechanisms. Since an understanding of the physics of breechblows is incomplete, a computer code capable of accurately describing breechblow phenomena clearly cannot be formulated at this time. Intuition-based physical mechanisms can, however, be postulated and theoretically probed under simplifying assumptions by minor modification of two-phase flow, interior ballistics models capable of treating flamespread and pressure wave phenomena. Those mechanisms appearing to possess significant potential for causing excessive pressures then warrant a more rigorous treatment.

IV. NUMERICAL INVESTIGATION OF BREECHBLOW-INDUCING PROCESSES

Summary of the NOVA Code. The particular model employed in this study is known as the NOVA code and has been documented at various stages of development [4-7]. NOVA consists of an unsteady, two-phase flow treatment

[4] *Gough, P.S. and Zwarts, F.J., "Theroetical Model for Ignition of Gun Propellant," SRC-R-67, Space Research Corporation, North Troy, Vermont, December 1972.*

[5] *Gough, P.S., "Fundamental Investigation of the Interior Ballistics of Guns: Final Report," IHCR 74-1, Naval Ordnance Station, Indian Head, Maryland, August 1974.*

[6] *Gough, P.S., "Computer Modeling of Interior Ballistics," IHCR 75-3, Naval Ordnance Station, Indian Head, Maryland, October 1975.*

[7] *Gough, P.S., "Numerical Analysis of a Two-Phase Flow with Explicit Internal Boundaries," IHCR 77-5, Naval Ordnance Station, Indian Head, Maryland, April 1977.*

of the gun interior ballistics cycle formulated under an assumption of one-dimensional flow.* The balance equations for each of the phases (treated as interpenetrating media) describe the evolution of averages of flow properties, these averages being taken over regions large enough to contain many particles. Constitutive laws include a co-volume equation of state for the gas and an incompressible solid phase. Compaction of an aggregate of particles is allowed, with intergranular stress being represented as a function of bed porosity. Interphase drag is represented by reference to the empirical correlations of Ergun[8] and Andersson[9] for fixed and fluidized beds, respectively. Similarly, interphase heat transfer is described according to Denton[10] or Gelperin-Einstein[11].

Functioning of the igniter system is included by providing as input an experimentally-determined, mass-injection rate as a function of position and time. Local grain temperature follows from the heat transfer correlation and the unsteady heat conduction equation for the solid phase, with ignition based on a surface temperature criterion. Propellant combustion is then assumed to follow a simple bP^n burning rate law (where P is the local gas pressure, and n and b are exponential and pre-exponential factors obtained by best-fit procedures to independent test data).

A unique characteristic of this code is the explicit treatment of internal boundaries defined by gas/mixture and mixture/mixture interfaces. In addition to increasing numerical accuracy, this technique allows for treatment of multiple charges of differing propellant configural and compositional characteristics. Also included is a lumped parameter treatment of the inertial and compactibility characteristics of any filler elements present between the propellant bed and the projectile base.

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[8] *Ergun, S., "Fluid Flow Through Packed Columns," Chem. Engr. Progr. Volume 48, 1952, pp. 89-95.*

[9] *Andersson, K.E.B., "Pressure Drop in Ideal Fluidization," Chem.Engr. Sci., Volume 15, 1961, pp. 276-297.*

[10] *Denton, W.H., "General Discussion of Heat Transfer," Inst. Mech. Engr. and Am. Soc. Mech. Engr., London, 1951.*

[11] *Gelperin, N.I. and Einstein, V.G., "Heat Transfer in Fluidized Beds," Fluidization, edited by J.F. Davidson and D. Harrison, Academic Press, 1971.*

*Actually, one-dimensional with area change.

Numerical solutions are obtained by a finite-difference approach, making use of a modified MacCormack scheme[12] for points in the interior of the mixture regions and the method of characteristics at the boundaries, The latter technique is modified to make direct reference to the solid phase continuity and momentum equations when the system of balance equations loses total hyperbolicity (as when the mixture contains a dispersed aggregate).

The Role of Ignition. Application of the NOVA code to the current study was first made to assess the predicted impact of ignition system performance on maximum chamber pressure. Localized ignition has long been known to significantly affect the level of pressure waves in guns[13-14], and it was felt that the pressure dependence of solid propellant burning rates could provide a sufficient feedback mechanism to result in excessive pressure levels associated with such wave fronts. To test this hypothesis, a series of NOVA calculations was performed, using as a baseline nominal data for a high-performance 155-mm howitzer (Table I). In the first case, uniform ignition of the entire propellant bed was assumed. As seen in Figure 8a, only minor longitudinal pressure waves are predicted, those presumably being associated with charge motion allowed by an initial gap between the propellant bag and the projectile base. In the second calculation (Figure 8b), a base ignition profile was assumed, all other parameters being the same. In the third calculation (Figure 8c), a very harsh, localized base ignition was assumed as input to the code. The level of pressure waves, as manifested in predicted breech and chamber mouth pressure-time curves, increased in the expected manner as the ignition event became more localized. However, no accompanying increases in maximum chamber pressure were predicted. Localized ignition alone thus appears insufficient to cause excessive chamber pressures - at least for this configuration.

Investigation of an 8-Inch Breechblow. To further probe this question, let us consider the case history of an actual breechblow incident and attempt to determine potential mechanisms for its occurrence. The firing of interest involves a charge sensitivity firing in which localized base ignition was believed to have initiated the chain of events leading to the breechblow. The firing was conducted in an 8-Inch, M110E2 Howitzer and involved an M188E1 (Zone 9) Propelling Charge, temperature-conditioned to -46°C. An intentional modification to the centercore ignition charge apparently led to base ignition as the principal mode of initiation. Pressure-time records up to the time of weapon failure are presented in

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[12] *MacCormack, R.W., "The Effects of Viscosity in Hypervelocity Impact Cratering," AIAA 7th Aerospace Sciences Meeting, Paper 69-354, 1969.*

[13] *Heddon, S.E., And Nance, G.A., "An Experimental Study of Pressure Waves in Gun Chambers," NPGR-1534, Naval Proving Ground, Dahlgren, Virginia, April 1957.*

[14] *Kent, R.H. "Study of Ignition of 155-mm Gun," BRL-R-22, U.S.A. Ballistic Research Laboratories, Aberdeen Proving Ground, Maryland, October, 1935 (AD494703).*

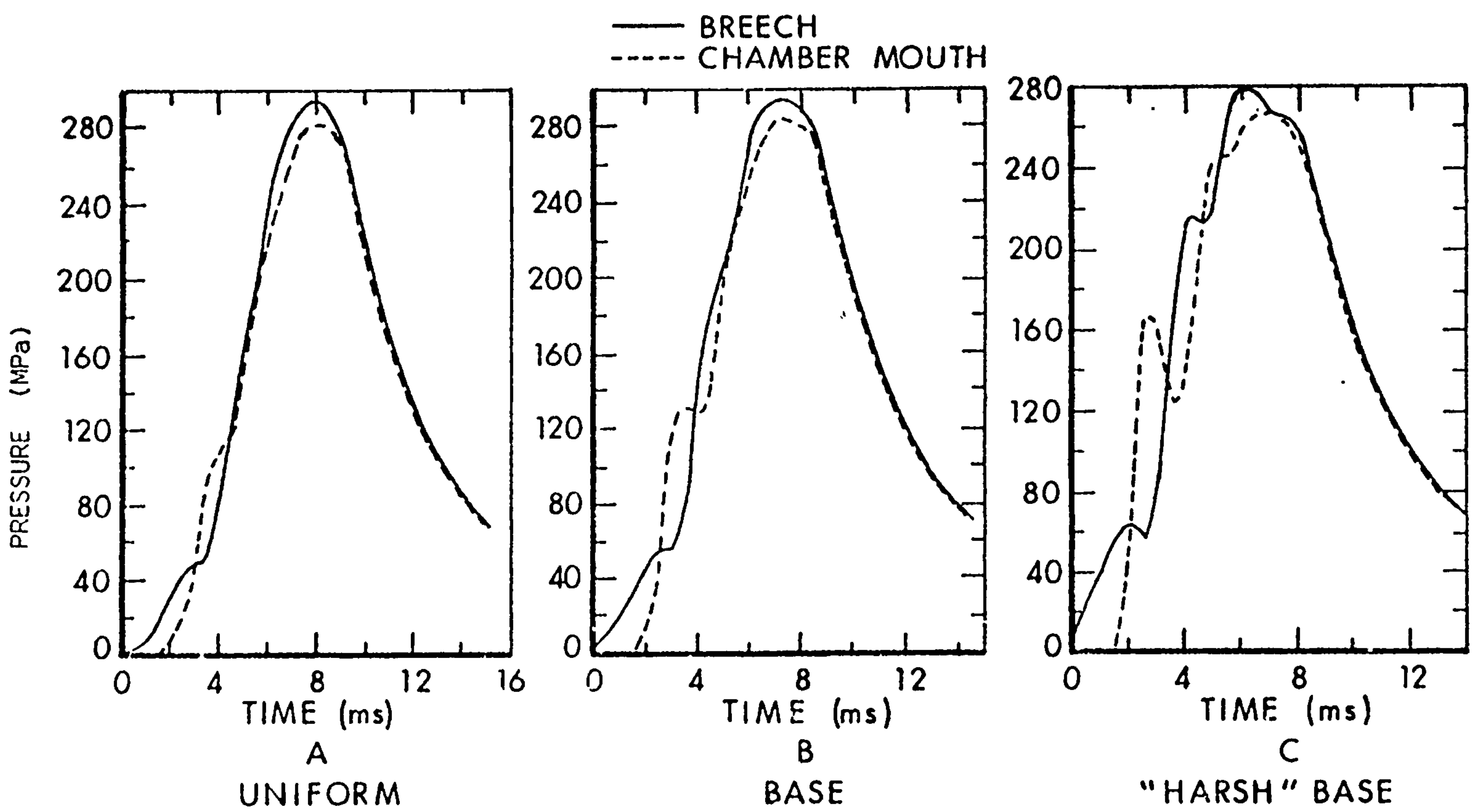

Figure 8. Predicted Effect of Ignition in a 155-mm Howitzer (Nominal High Performance Propelling Charge)

Figure 9. Copper crusher gage data and results from several analyses of tube deformation suggest that pressures reached at least 910 MPa before separation occurred at the breech. The chamber mouth record is characterized by an extremely rapid pressurization event (though instrumentation overshoot precludes precise quantitative analysis), followed by a somewhat unsteady but continued increase in pressure even prior to the return of the reflected wave from the breech end of the chamber.

Efforts were made to provide a computer simulation of functioning of the M188E1 (Zone 9) Charge with varying degrees of localization of base ignition. A summary of input data used is provided in Table II. As shown in Figure 10, the results of these calculations duplicate the trend manifested by the 155-mm calculations: increasing pressure wave levels with no accompanying increases in maximum chamber pressures. In actual fact, a slight decrease in maximum pressure is predicted!

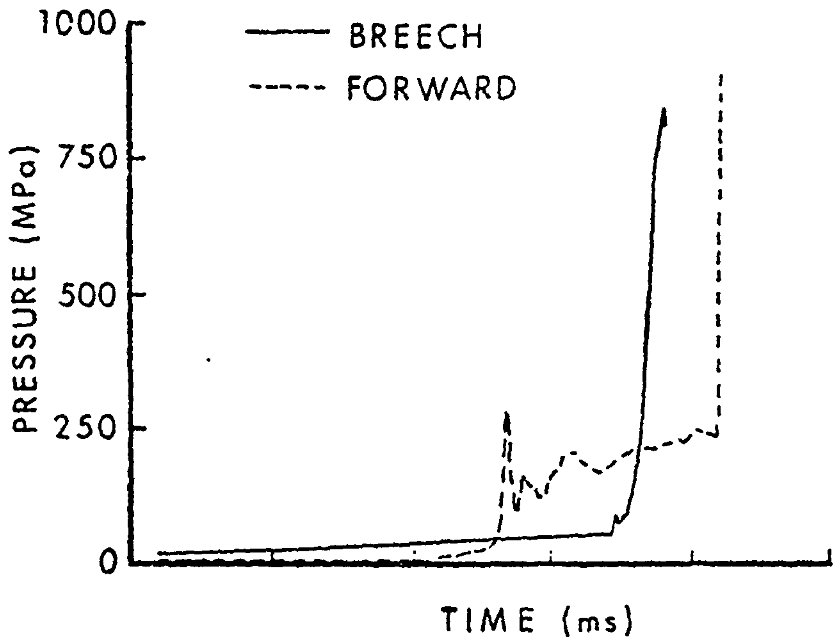

Figure 9. Pressure-Time Profiles for the 8-Inch, M110E2 Howitzer Breechblow (M188E1 (Zone 9) Propelling Charge)

Table I. Input Data Summary - 155-mm Howitzer

Number of Grid Points	35
Speed of Sound in Packed Bed	442 m/s
Settling Porosity of Nominal Composition	0.527
Left Hand Boundary of Propellant	0.64 cm
Right Hand Boundary of Propellant	55.25 cm
Mass of Propellant	9.89 kg
Density of Propellant	1.58 g/cm^3
Number of Perforations	7
Outside Diameter of Grain	1.07 cm
Perforation Diameter	0.086 cm
Length of Grain	2.43 cm
Burning Rate Coefficient	0.387 $cm/s\ (MPa)^n$
Burning Rate Exponent	0.70
Ignition Temperature	450 K
Chemical Energy Released in Burning	4426 J/g
Molecular Weight	23.46
Specific Heat Ratio	1.24
CoVolume	0.945 cm^3/g
Initial Position of Projectile	82.2 cm
Mass of Projectile	43.1 kg

Table II. Input Data Summary - 8-inch Howitzer

Number of Grid Points	35
Speed of Sound in Packed Bed	442 m/s
Settling Porosity of Nominal Composition	0.597
Left Hand Boundary of Propellant	2.51 cm
Right Hand Boundary of Propellant	81.28 cm
Mass of Propellant	18.91 kg
Density of Propellant	1.58 g/cm^3
Number of Perforations	7
Outside Diameter of Grain	1.24 cm
Perforation Diameter	0.122 cm
Length of Grain	2.84 cm
Burning Rate Coefficient	0.298 $cm/s\ (MPa)^n$
Burning Rate Exponent	0.716
Ignition Temperature	450 K
Chemical Energy Released in Burning	4468 J/g
Molecular Weight	23.0
Specific Heat Ratio	1.245
CoVolume	0.892 cm^3/g
Initial Position of Projectile	84.6 cm
Mass of Projectile	90.7 kg

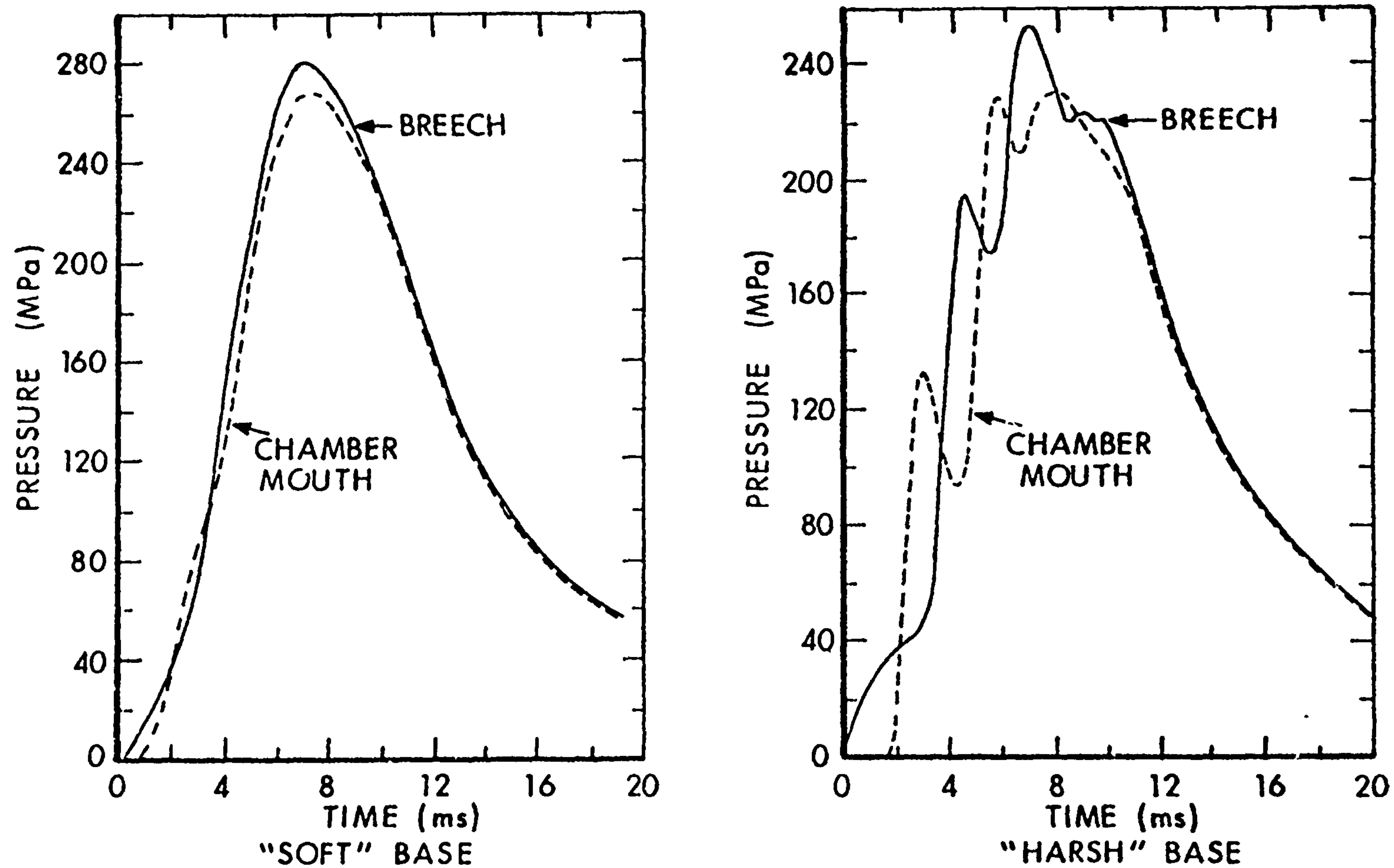

Figure 10. Predicted Effect of Ignition in the 8-Inch, M110E2 Howitzer (M188E1 (Zone 9) Propelling Charge)

What then is the missing link between pressure waves and breechblows? It is apparent that some vital physical processes are missing in the simulation procedures. By some mechanism, gas production rates must be dramatically increased, at least in the vicinity of the pressure wave front. Of course, one known weakness in the model involves use of the simple bP^n burning rate law. Selection of this form has been motivated primarily by ease of implementation and the availability of data to facilitate its use. The combustion process, however, is not really modeled with such a representation, and no capability is provided to account for any transient effects such as might be imposed by a passing pressure front. It is just such an environment, characterized by extremely high pressurization rates accompanying the pressure wave dynamics, that is often encountered with base ignition of high loading density propelling charges.

Numerous combustion or burning rate models have been proposed for treatment of the transient burning response[15-18]. Recent calculations by Kooker and Nelson[19] involving application of the Levine-Culick combustion model[17] to a closed bomb problem have indicated the possibility of low-pressure burning rate multiples on the order of 2-3, with virtually no effect on steady state burning rate values at pressures greater than 20-30 MPa. (Of course, one can readily conceptualize problems involving severe pressure transients and accompanying burning rate enhancement at much higher pressures). An effort to couple the Zeldovich combustion model to the NOVA code is described by Nelson et al[21]. Progress to date has not been sufficient for treatment of the breechblow problem.

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[15] *Paul, B.E., Levin, R.L., and Fong, L.Y., "A Ballistic Explanation of the Ignition Pressure Peak," AIAA Solid Propellant Rocket Conference, Paper 64-121, 1964.*

[16] *Krier, H., Tien, J.S., Sirignano, W.A., and Summerfield, M., "Non-Steady Burning Phenomena of Solid Propellants," AIAA Journal, Volume 6, Number 2, February 1968, pp. 278-285.*

[17] *Levine, J.N. and Culick, F.E.C., "Nonlinear Analysis of Solid Rocket Combustion Instability," AFRPL-TR-74-45, Air Force Rocket Propulsion Laboratory, Edwards AFB, California, October 1974.*

[18] *Kooker, D.E. and Zinn, B.T., "Numerical Investigation of Nonlinear Axial Instabilities in Solid Rocket Motors," BRL-CR-141, USA Ballistic Research Laboratories, Aberdeen Proving Ground, Maryland, March 1974.* (AD #776954)

[19] *Kooker, D.E. And Nelson, C.W., "Numerical Solution of Three Solid Propellant Combustion Models During a Gun Pressure Transient," BRLR 1953, USA Ballistic Research Laboratories, Aberdeen Proving Ground, Maryland, January 1977.* (AD #A035250)

[20] *Zeldovich, Y.B., "On a Burning Rate Under Nonsteady Pressures," Zhurnal Prikladnoi Mekhaniki i Technischeskoi Fiziki, 3, 126, 1964.*

[21] *Nelson, C.W., Robbins, F.W., and Gough, P.S., "Predicted Effects of Transient Burning on Gun Flamespreading," 14th JANNAF Combustion Meeting, CPIA Publication 292, December 1977, pp. 315-333.*

A very simple and admittedly naive approximation of this behavior can be achieved through use of a burning rate additive constant ($r = a + bP^n$), which also has little relative effect at higher gun pressures. The low pressure burning rate enhancement is not limited though to the region of propellant experiencing passage of the pressure wave front; rather, augmentation is simply a function of the local ambient pressure but not of pressurization rate. Nevertheless, calculations were performed employing additive burning rate constants leading to low-pressure (14 MPa) burning rate multiples as high as 3. The results, presented in Figure 11, reveal a significant impact on resulting maximum chamber pressures, although no runaway effect to breechblow levels is suggested.

A consideration of other potential mechanisms capable of increasing gas production rates by any significant amount led to only one serious addition: increased burning surface via grain fracture. This additional physical mechanism is certainly possible in the light of a previous history of low temperature grain fracture for triple base propellants[22]. Gun propellants in general are known to become brittle at low temperatures[23]. This particular charge exhibited no peak pressure enhancement when fired hot, but similar modest levels of pressure waves were accompanied by maximum pressure increases at low temperatures.

The possible involvement of this mechanism in a breechblow incident was investigated experimentally by the U.S. Navy with respect to a 76-mm gun malfunction at the Naval Weapons Laboratory, Dahlgren, Virginia in 1972[24]. Air gun tests were performed in which single grains of M6 propellant were impacted on a steel plate to determine breakup characteristics at different temperatures. Predictably, typical results (Figure 12) indicated that the velocity required to cause grain fracture decreases with temperature. Impact velocities as low as 30 m/sec were seen to result in fracture at temperatures of about -10°C, considerably warmer than the -46°C condition for the 8-Inch, M110E2 breechblow.

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[22] *Russell, K.H. and Goldstein, H.M. "Investigation and Screening of M17 Propellant Production for Lots Subject to Poor Low Temperature Performance," DB-TR-7-61, Picatinny Arsenal, Dover, New Jersey, June 1961.*

[23] *Schubert, H. and Schmitt, D., "Embrittlement of Gun Powder," Proceedings of the International Symposium on Gun Propellants, October 1973, p. 2.11.*

[24] *Olenick, P.J. "Investigation of the 76-mm/62 Caliber Mark 75 Gun Mount Malfunction," NSWC/DL TR-3144, Naval Surface Weapons Center, Dahlgren, Virginia, October 1975.*

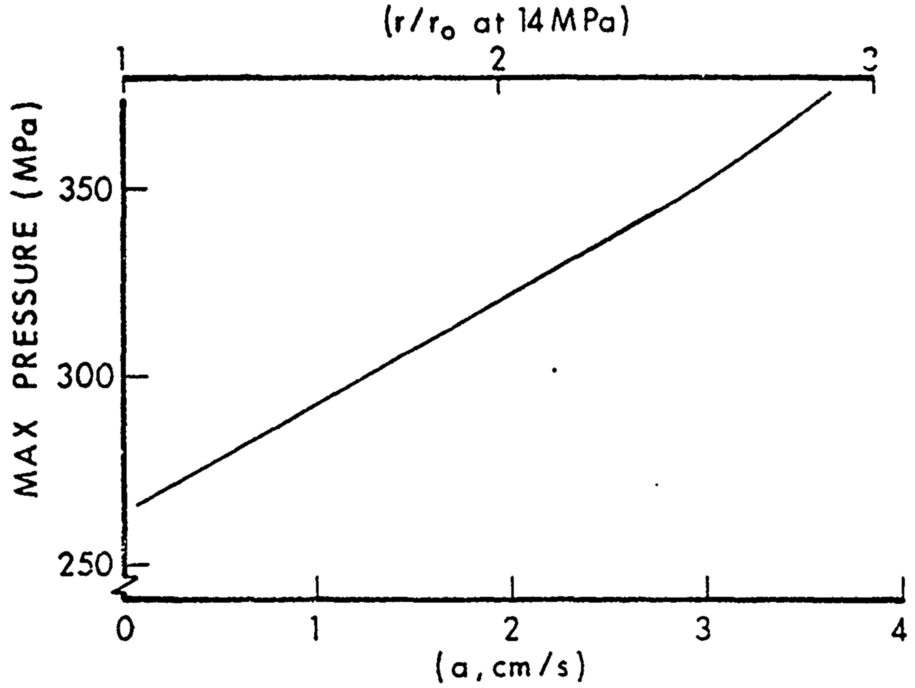

Figure 11. Predicted Effect of Burning Rate Augmentation (Additive Constant)

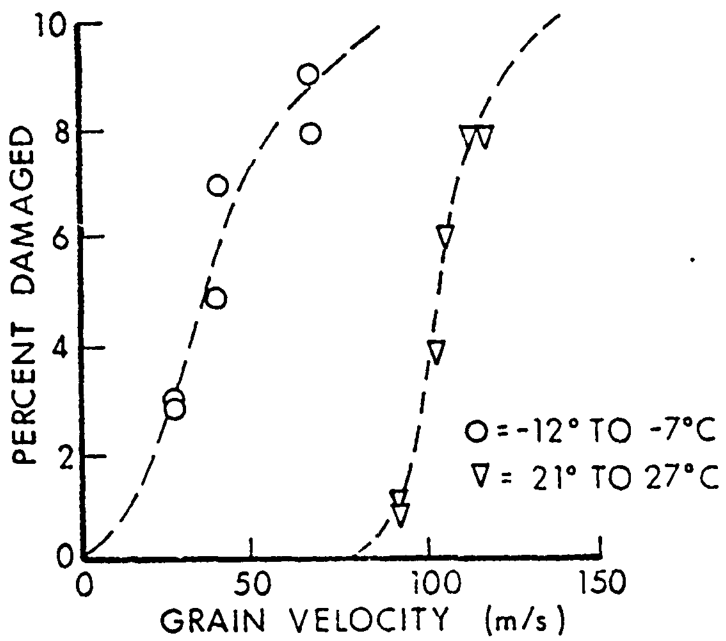

Figure 12. Air Gun Impact Test Results - M6 Propellant (From Ref. 24)

A detailed treatment of the effects of grain fracture on the growth of pressure waves is difficult for many reasons, not the least of which is simply our inability to describe the extent and geometry of fractures which might occur during the course of the interior ballistic cycle. If we, however, allow ourselves to be guided by intuition, the problem can be approached in a simplified manner as shown in Figure 13. Prior to ignition of the M188E1 Charge in the M110E2 Howitzer, several centimeters of free space are present between the front end of the charge and the projectile base. As the firing cycle proceeds, a portion of the propellant charge is thrust forwards (by mechanisms previously described), striking the projectile base at predicted velocities of at least 60 m/s for base-ignition configurations. If, during a NOVA code simulation of the problem, the calculation is temporarily halted at the moment the leading edge of the propellant bed strikes the projectile base, the geometry of a certain portion of the grains can be reset to simulate the effects of grain fracture. Continuation of the calculation from that point should then provide some information regarding the potential importance of this mechanism.

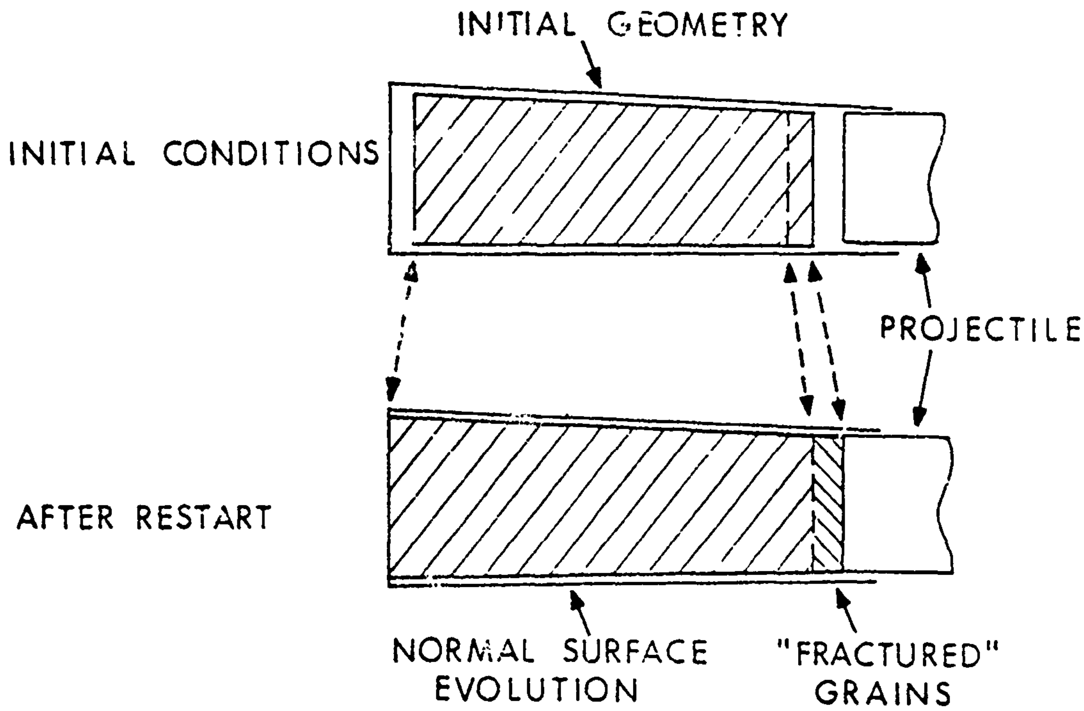

Figure 13. Treatment of Grain Fracture with the NOVA Code

The task of describing the altered distribution of propellant grain geometries after fracture is largely one of guesswork. Numerical as well as physical limitations motivated the selection of a 5.1-cm thick disc of propellant at the front of the bed to undergo "fracture". Propellant grain geometries in this region were redefined such that the available burning surface in this region was multiplied by factors from 2 to 5. With respect to the total burning surface provided by the entire charge, these changes represent increases of from 6 to 25 percent. Figure 14 summarizes the results from a series of NOVA code calculations performed to assess the impact of this range of local increases in surface area on maximum chamber pressure. Clearly, pressure levels capable of causing weapon damage are predicted to be attainable via this mechanism. Interestingly enough, similar increases in surface area <u>uniformly distributed</u> over the entire propellant charge are predicted to result in comparatively mild increases in chamber pressure. Apparently, the effect becomes pronounced only when the increased surface area occurs coincidentally with the high local pressures accompanying flow stagnation at the projectile base. Incidentally, fractured grains with fresh surface area suddenly exposed to a high pressure/high temperature environment would ignite quickly and be extremely susceptible to transient burning rate effects (from a thermal wave standpoint).

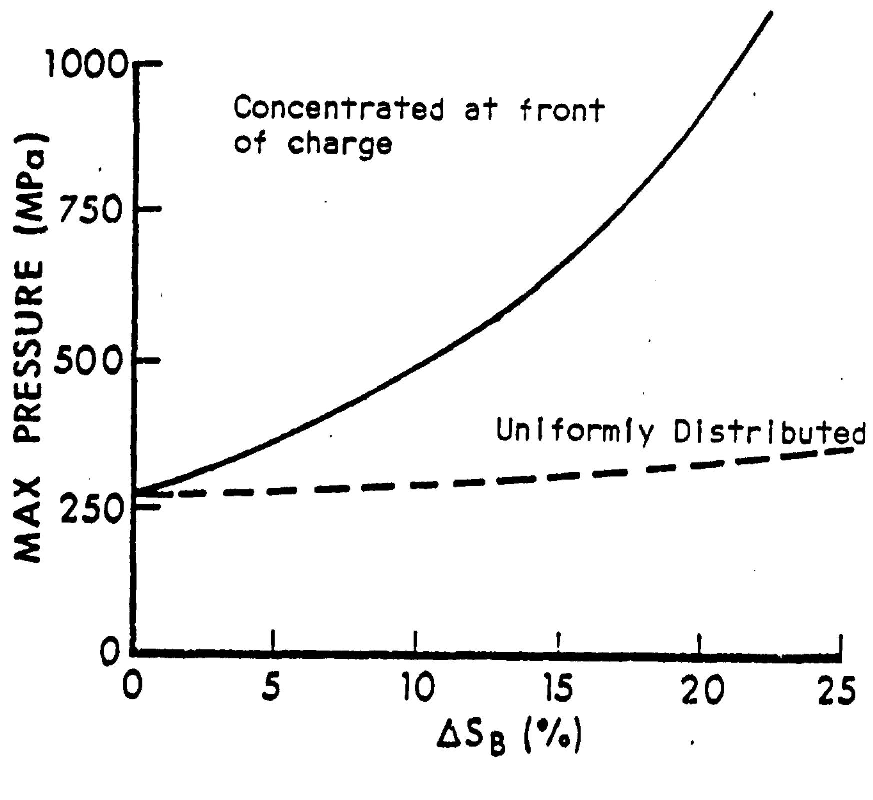

Figure 14. Predicted Effect of Grain Fracture

V. CONCLUSIONS

The above studies unfortunately have not brought us to the point where we can quantitatively describe those processes responsible for breechblows. Nevertheless, we can discuss a postulated explanation for their occurrence, consistent with both experimental observation and the results of the preceding calculations. Let us begin by noting a comparison of theory to experiment, aided by the results presented in Figure 15. First, it appears that pressure waves set up by strong, localized ignition of the propellant bed do not directly lead to breechblow pressure levels - at least, not without assistance from some intermediate mechanism. Second, the addition of increased low-pressure burning rates (by whatever mechanism) further increases wave dynamics and can raise maximum pressures significantly; however, burning rate multiples in excess of 3 must be invoked to lead to breechblows. Finally, a "runaway" pressurization profile is predicted to accompany a 16-percent increase in burning surface, if the increase is concentrated in the front of the propellant bed.

We now postulate the following qualitative mechanism for pressure-wave-induced, peak chamber pressure enhancement:

(1) Localized (usually base) ignition plus perhaps configural aspects of the charge/chamber interface lead to the formation of strong longitudinal pressure waves.

(2) The pressure gradient and interphase drag forces accompanying these waves accelerate the propellant grains to impact the projectile base (and perhaps the spindle or breechblock).

(3) At some temperature-dependent, impact-velocity threshold, propellant grains fracture and expose additional burning surface.

(4) This increased surface area is ideally located with respect to high local pressure levels and pressurization rates for coupling with pressure-dependent and transient burning effects, leading to very strong amplification of pressure waves and subsequent maximum pressure levels.

From a pragmatic standpoint, this qualitative explanation suggests several approaches toward minimizing peak chamber pressure enhancement. The most obvious one is, of course, to minimize the creation of pressure waves by increasing the functioning reliability of centercores. Another approach is to minimize the contribution from charge configurational aspects such as ullage. Eliminating ullage near the projectile base may be of even more direct benefit by reducing the velocity of grains impacting the projectile, perhaps below the critical threshold velocity for grain fracture. Finally, raising this threshold velocity by improved processing or formulation changes ought not to be neglected.

With respect to modeling capabilities, continued work concerning treatment of grain fracture and transient burning is clearly warranted.

However, until such time that a quantitative description of these processes is available, with what tools is the charge designer left for safety analysis of candidate designs? Apparently, the application of a $-\Delta p_i$ criterion as described earlier in this paper must now be rethought to include the effects of temperature on the relationship between pressure wave levels and maximum chamber pressure. The practicality of this modification depends, of course, on individual charge/weapon characteristics. Unfortunately, the only alternative available at this time is the firing of very large quantities of charges to statistically assess their safety. The costs associated with this approach, both in terms of dollars and time, motivate us strongly to complete our physical description to the point that an appropriate safety criterion can be clearly identified and easily applied.

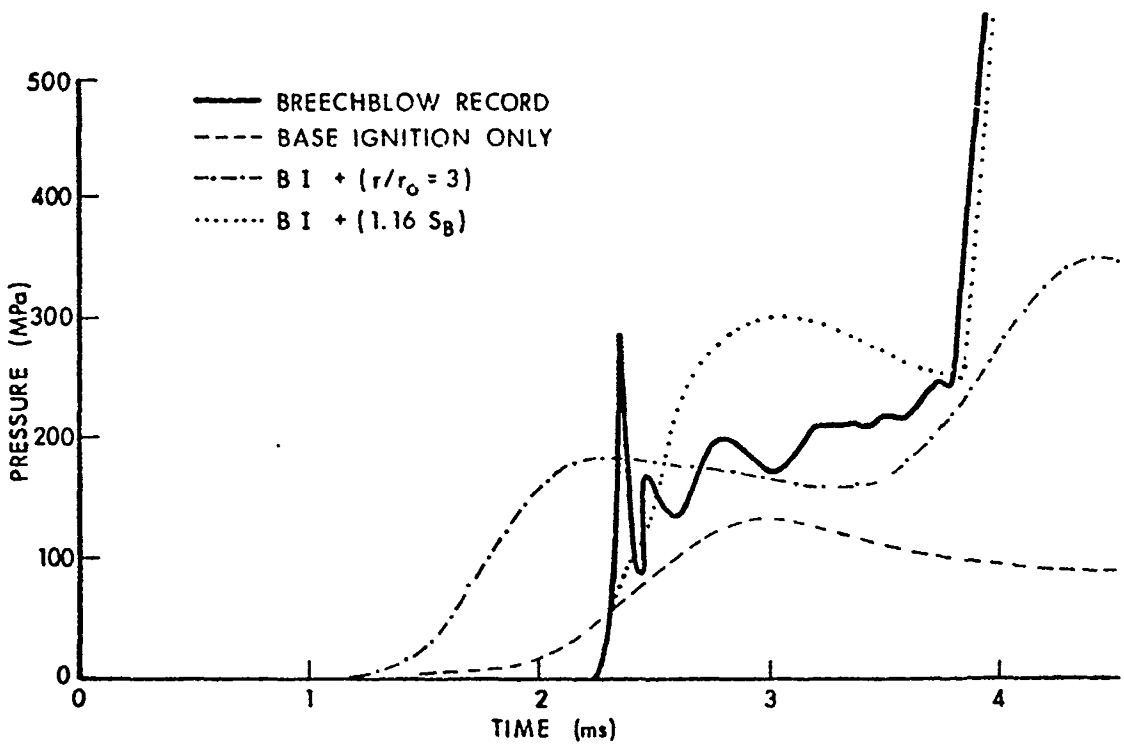

Figure 15. Comparison of Chamber Mouth Pressure-Time Records-Experimental and Predicted (8-Inch, M110E2 Breechblow)

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